DIAMOND DETECTOR: MEASURING BEAM INTENSITY

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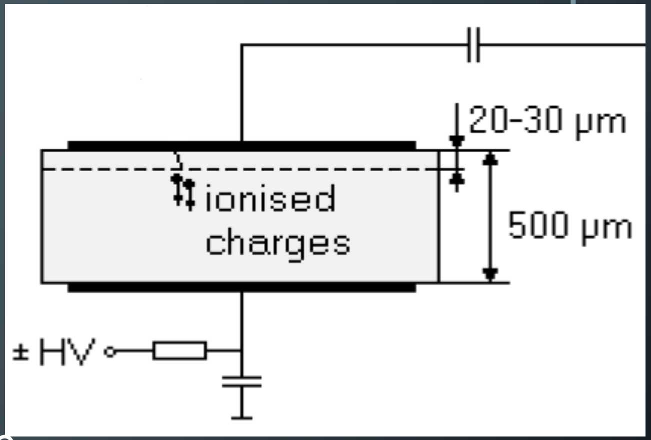
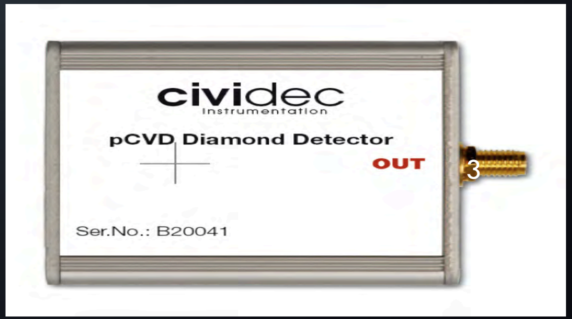
PURPOSE OF PROJECT

- There are several ways of measuring beam intensity. One of those ways is through the use of an instrumentation device called a Diamond Detector.
- With the purpose of looking for a replacement for the current method in measuring beam intensity for the Switchyard beamline, which involves using Secondary Emissions Monitors (SEMs), the Diamond Detector may offer a less expensive and more effective way of measuring beam intensity.
- Also, the ability to measure the micro-bunch structure of the beam is possible because of the fast measurement capabilities that the Diamond Detector has.

HOW THE DIAMOND DETECTOR WORKS



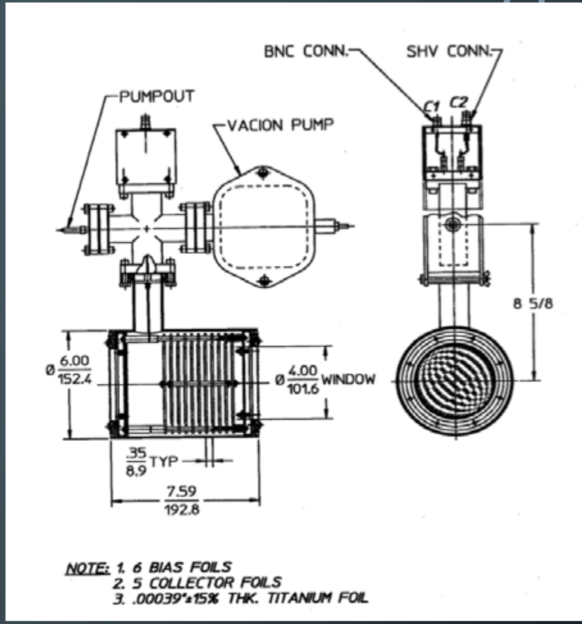
- Charged-particle solid-state detector
- High radiation tolerance, which makes it useful to use in an accelerator beamline
- Bias voltage applied across the diamond
- Charged particles ionize the diamond material and create free charge carriers (electron-hole pairs)
- The drift of the charges between the electrodes creates a signal of current that can be measured
  - In some cases, the current signal from the diamond detector is relatively small (picoamp range), so a low noise current amplifier would be used in combination with the diamond detector
- sCVD vs pCVD (single crystal diamond vs. polycrystalline diamond)
- High signal to noise ratio



HOW THE DIAMOND MATERIAL IS MADE

- The diamond technology is made by a chemical vapor deposition (CVD) process.
- CVD diamonds are placed in tightly controlled growth and quality conditions for the manufacturing of the diamond material that the customer asks for
- A CVD diamond is produced in a vacuum with carbon atoms supplied from gases like methane. The ability to control the gas purity makes the diamond effective for applications in particle detectors and other precise instruments.
- The diamond detector that I tested measures 1 x 1 cm^2 and was 500 micrometers thick

COMPARISON TO SEMS



- Secondary Emission Monitors
- The beam interaction with foils liberates electrons
- This leaves the foils with a positive charge which is measured by a current digitizer
- Calibration changes with time and beam position (with time secondary electron yield is less, so the SEMS are calibrated often)
- Large material in beam: ~10 titanium foils of approx. 5 mm thick
- More beam is lost/scatterred with SEMs than a Diamond Detector

KEITHLEY MODEL 6517B PICOAMMETER

- Voltage Source
- Capability of measuring in the picoamp range (very precise instrumentation for readout hardware), can measure temperature & humidity of an area, and can communicate with a computer via the General Purpose Interface Bus (GPIB) port

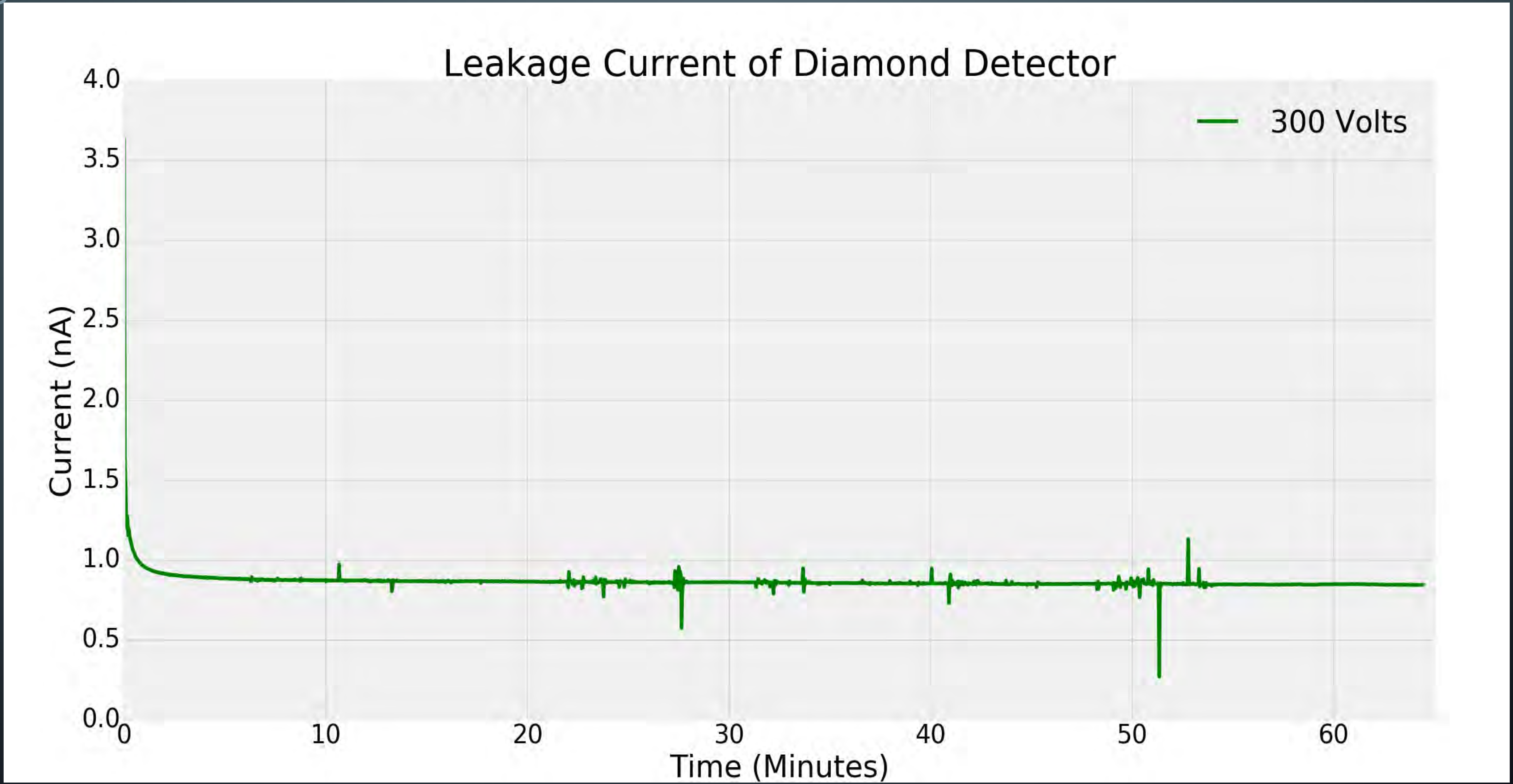
GPIB TO USB INTERFACE

- Baud rate
- CR & LF
- Address of GPIB to talk to electrometer

PyVISA

LEAKAGE CURRENT

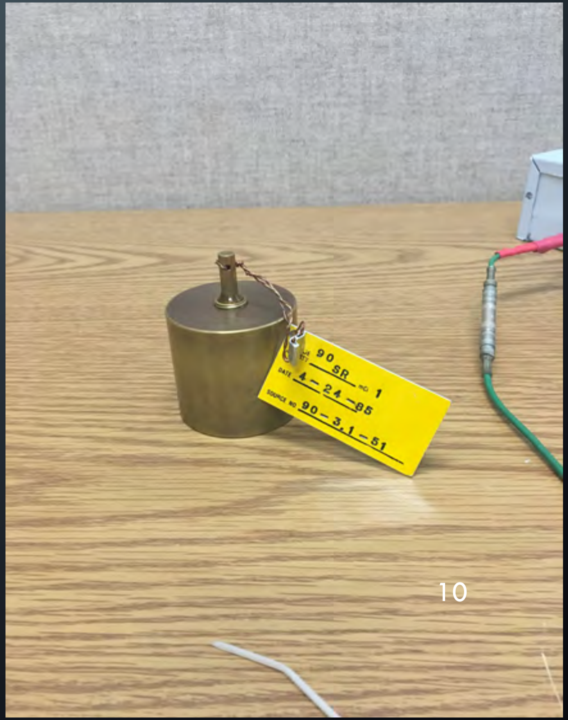
- The leakage current of a diamond detector occurs due to the limited electric conductivity inherent in semiconductor materials.
- It is necessary to reduce the leakage current to obtain a better signal to noise ratio from the Diamond Detector so measurements will be more accurate and proportional to the beam intensity

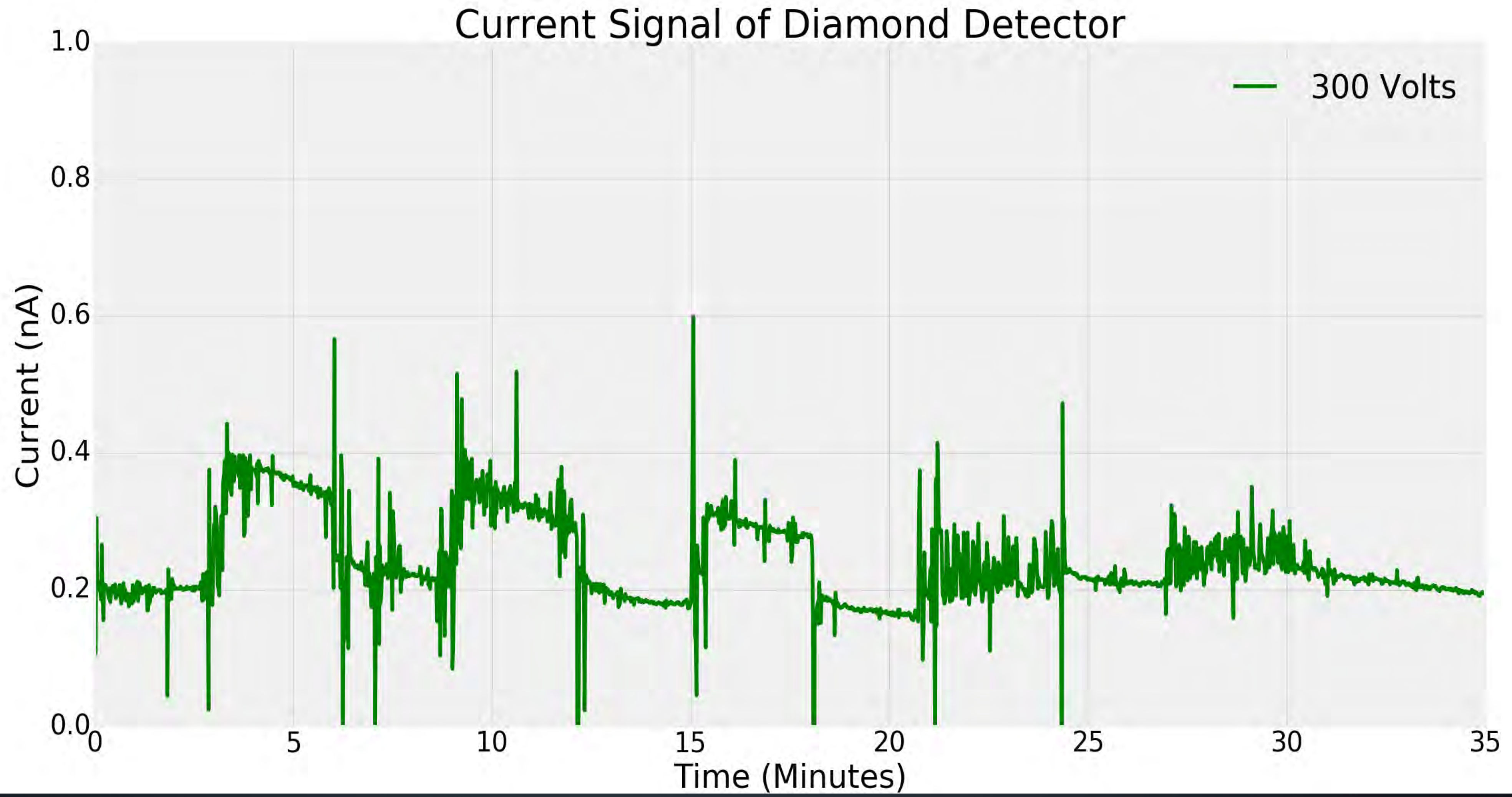

Leakage Current of Diamond Detector
300 Volts
Current (nA)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
60
Time (Minutes)

SR90 (STRONTIUM-90) RADIOACTIVE SOURCE

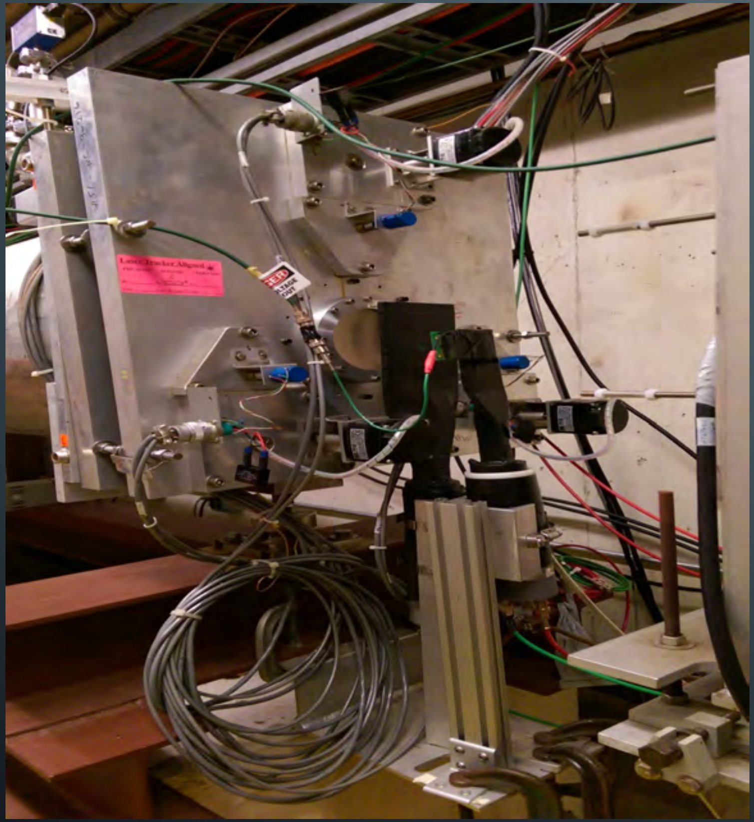
- Undergoes beta decay and radiates beta particles
- Decay energy of 0.546 MeV distributed among an electron, an anti-neutrino and the Yttrium-90 isotope
- Became a Source Monitor to handle the Strontium-90 source
- Simulated beam pulses by holding up the source closer and further away

$$ {}_{38}^{90}\mathrm{Sr} \rightarrow {}_{39}^{90}\mathrm{Y} + {}_{-1}^{0}e $$




Current Signal of Diamond Detector
300 Volts
Current (nA)
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
Time (Minutes)

SET UP AT FERMILAB TEST BEAM FACILITY (MTEST BEAMLINE)



ORC PROCESS

- An Operational Readiness Clearances (ORC) review had to be made by ES&H in order to place the diamond detector to test for measuring beam intensity
- We had to explain the purpose for placing the diamond detector in the beamline, its impact on the radiation environment and address electrical and safety hazards

RMS SCATTERING ANGLE DUE TO DIAMOND

$$E_{total} = E_{kinetic} + E_{rest}$$

$$\frac{E_{tot}}{E_{rest}} = \frac{\gamma * mc^2}{mc^2} = \gamma$$

$$\beta = \frac{v}{c}$$

$$\gamma = \sqrt{\frac{1}{1-\beta^2}}$$

$$\beta = \sqrt{1 - \frac{1}{\gamma^2}}$$

$$p = \gamma * mc$$

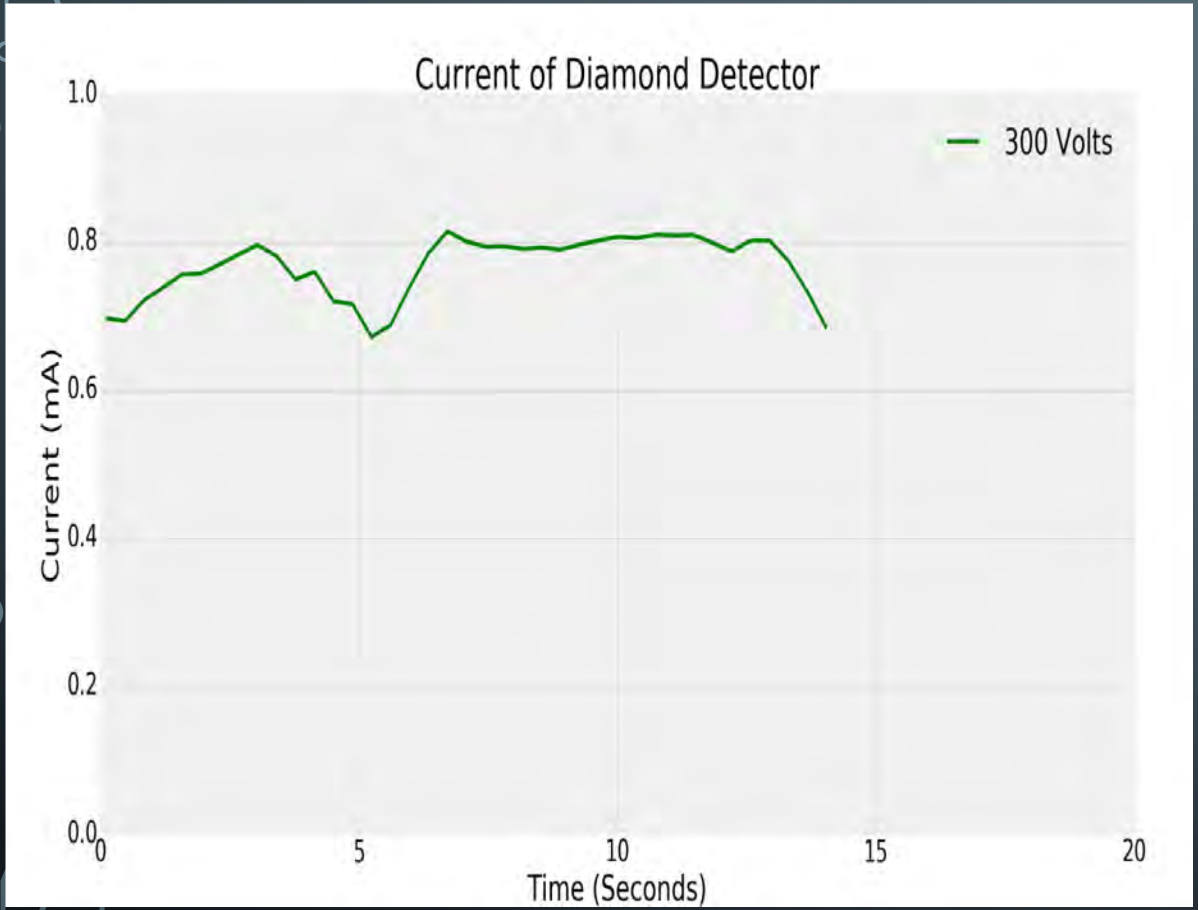
$$p = \frac{E_{total}}{c}$$

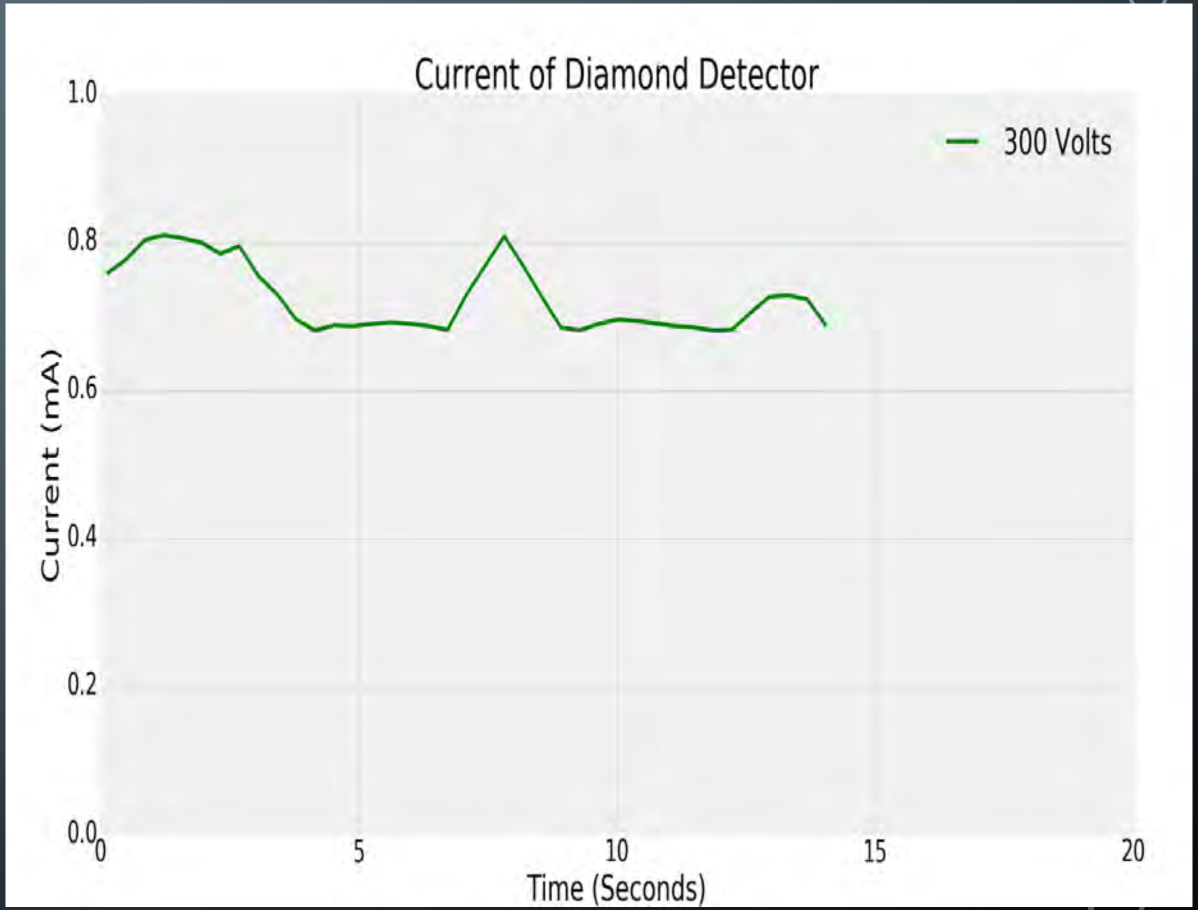
$$\Theta_{rms} = \frac{13.6\ MeV}{pv} z \sqrt{\frac{x}{X_0}} [1 + 0.038 ln(\frac{x}{X_0})]$$

POWER LOSS CALCULATION

- This another calculation needed for the diamond detector to be placed in MTEST
- Purpose: to figure out how much beam we are losing and the potential secondary radiation power
- Interaction length of 0.4%

TEST BEAM FACILITY RESULTS



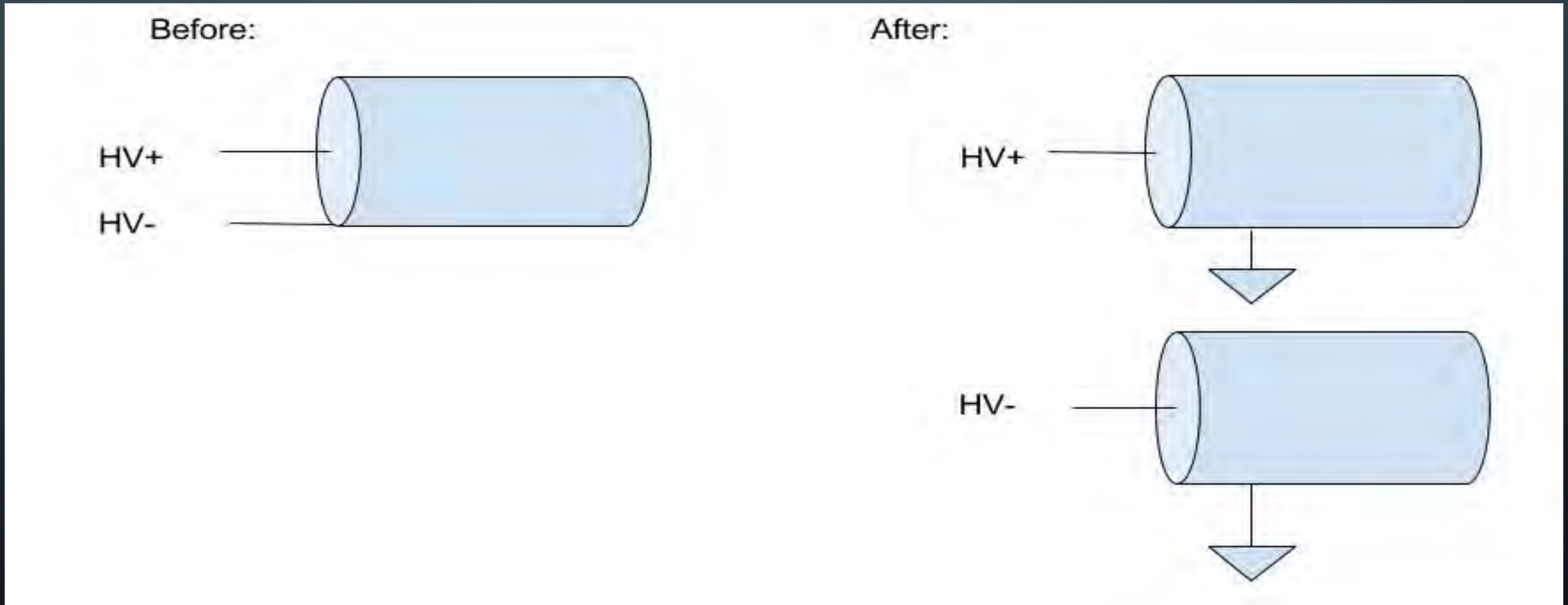


PROBLEM AT FERMILAB TEST BEAM FACILITY

- Did not achieve a high enough signal to noise ratio so that we could see the current signal from the diamond detector when a beam pulse went through the diamond material
- In order to carry out a high signal to noise ratio, we needed a better Faraday cage so the diamond detector wouldn't pick up noise from outside electric fields
  - A Faraday cage is used to block electric fields and is formed by conductive material
- We set out to use two coaxial cables for better shielding that would pick up less noise

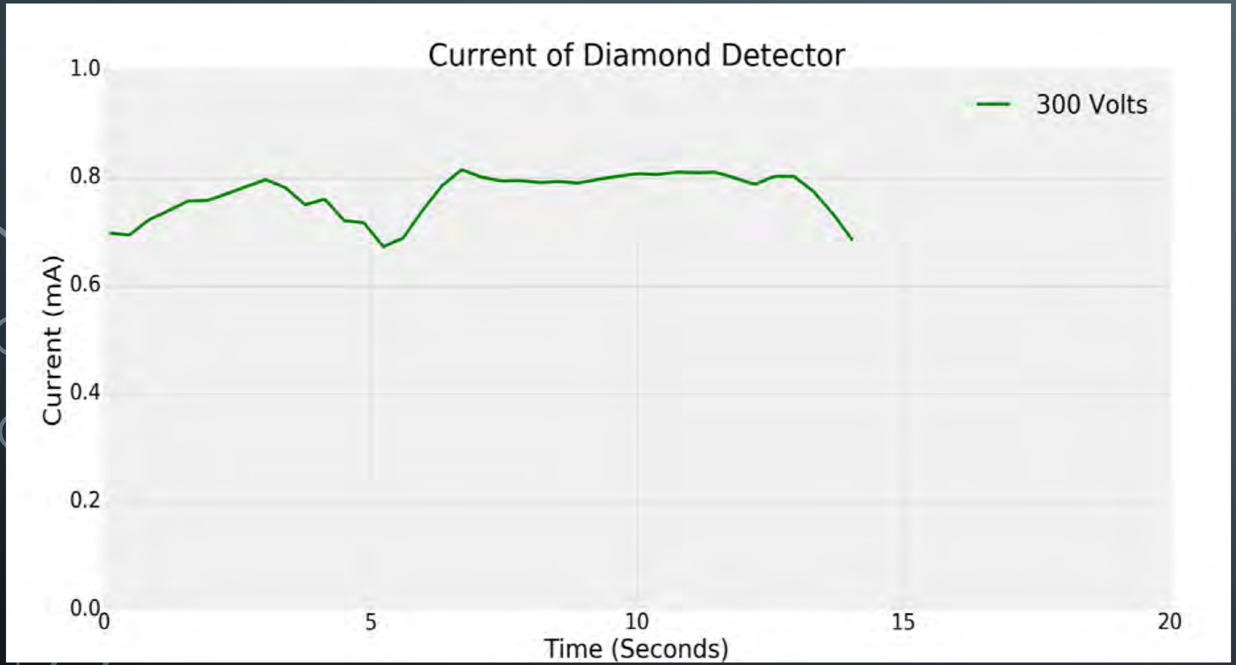
INSTRUMENTATION FIX

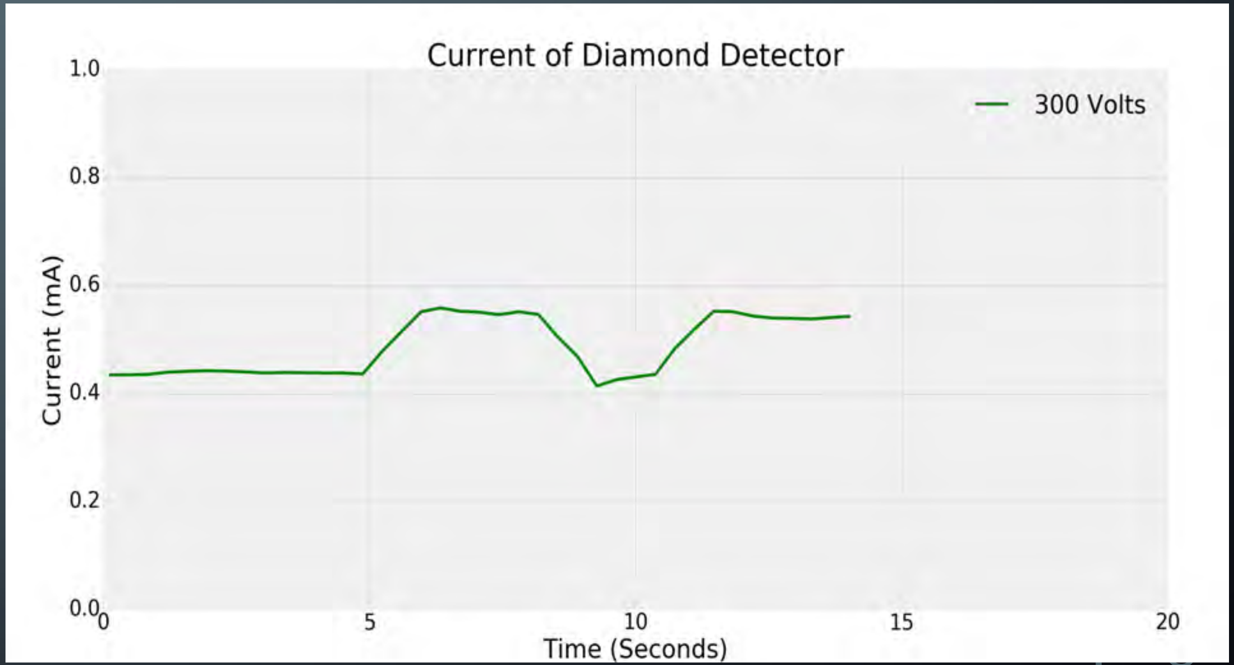
- The shielding from the RG-58 cables were now grounded so that our signal to noise ratio could be higher



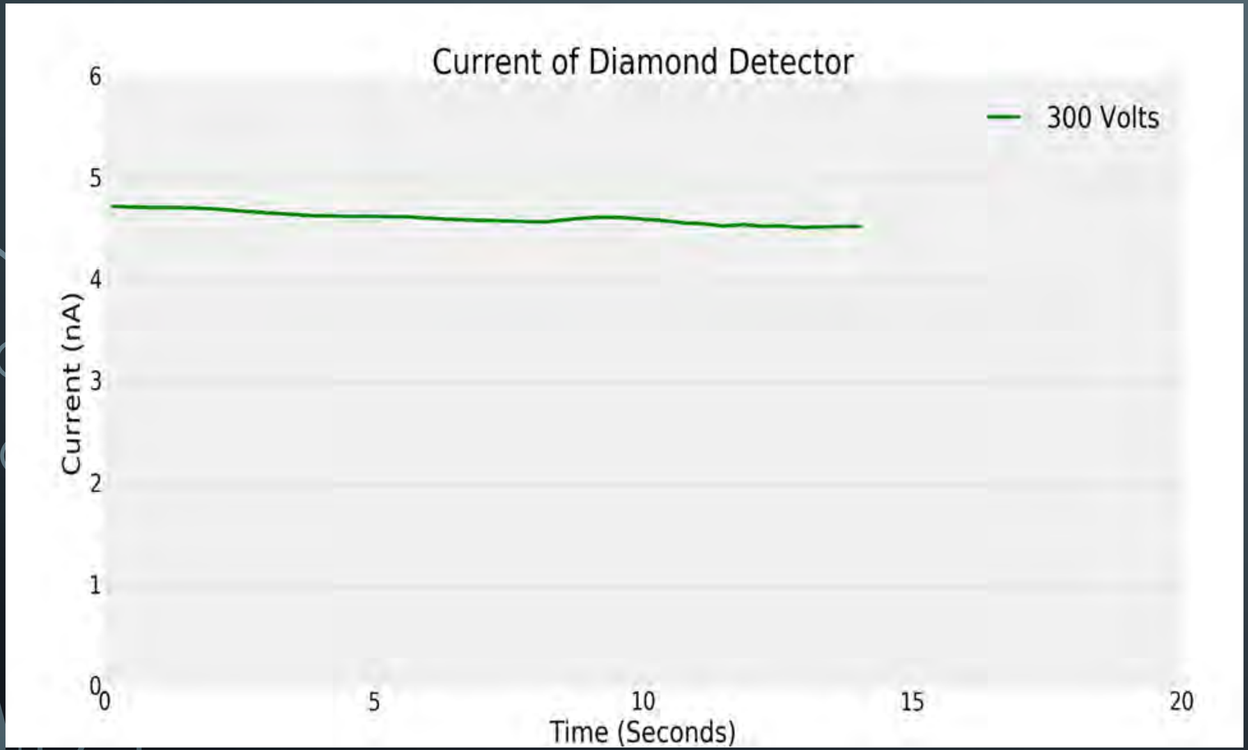
INSTRUMENTATION FIX

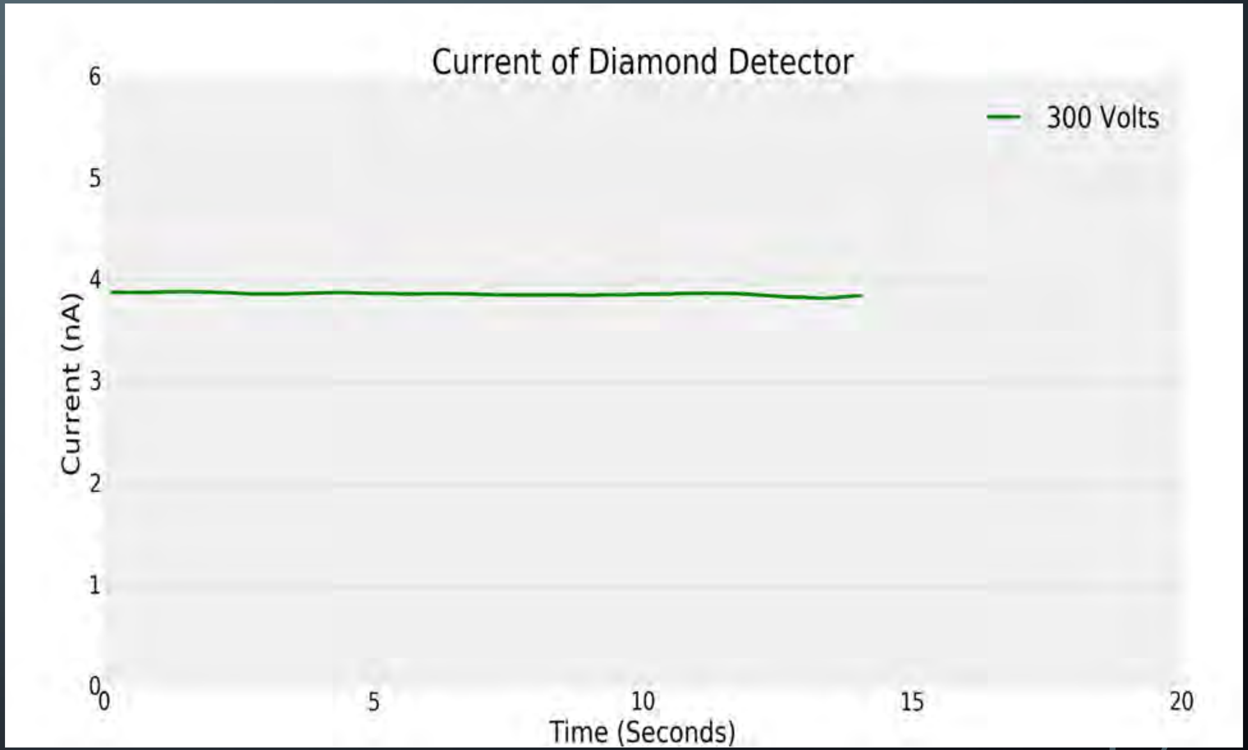
NOISE PICKED UP BY INSTRUMENTATION





NOISE WITH NEW INSTRUMENTATION





FUTURE DIRECTIONS

- We are looking to measure the micro-bunch structure of the beam using the diamond detector.
- We are also looking to discover the dynamic range of the Diamond Detector: can it read the intensity from a few hundred particles up to 10^{13} particles?
  - The diamond detector should be able to read this dynamic range from the current signal as the current signal should decrease or increase linearly, depending on the intensity of the beam.

PROBLEMS THAT MAY NEED TO BE ADDRESSED

- Calibration does change as time increases, which levels off, but still something to keep in mind
  - Long tem calibration? Does it drop off after a very long time?
  - Might need to be recalibrated as often as the SEMs
- Small current and high frequency
  - Readout hardware has to measure micro-bunch structure, so instrumentation has to be very precise in how it's made to readout current signal
- Expensive?
- Noise
  - Electromagnetic noise
    - On Diamond and cables? Better Faraday Cage?

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- Special thanks to: Gianni Tassoto, Richard Tesarek, Rick Pierce, David Peterson, Arden Warner

QUESTIONS?

REFERENCES

R.M. Zain et al. Leakage current measurements of a pixelated polycrystalline CVD diamond detector. IOPscience. 1-6., 2012

E. Griesmayer et al. High-Resolution Energy and Intensity Measurements with CVD Diamond at REX-ISOLDE. CERN. 1-12, 2009.

K.A. Olive et al. (Particle Data Group), Chinese Physics C38, 090001 (2014)

Concepts Rookie Book: http://operations.fnal.gov/rookie_books/concepts.pdf

BACKGROUND SLIDES

RMS SCATTERING ANGLE DUE TO DIAMOND

In [1]:
```
#RMS Scattering Angle Calculation
#do for 120 GeV beam
```

In [2]:
```
#Every particle has a non-zero amount of enery, this is known as the rest ener
gy.
#Due to the high particle energies and speeds in the accelerators,
#special relativity has to be taken into account to describe the accelerated p
articles
#This brings us to using a relativistiv factor, gamma, which gives us a differ
ent
#way to express the total energy.
```

$$E_{rest} = mc^2$$

$$E_{total} = \gamma * mc^2$$

$$E_{total} = E_{kinetic} + E_{rest}$$

RMS SCATTERING ANGLE DUE TO DIAMOND

```
In [3]: #Using the previous definitions of the energies, we can calculate gamma.
```

$$\frac{E_{tot}}{E_{rest}} = \frac{\gamma * mc^2}{mc^2} = \gamma$$

```
In [4]: E_rest = 938E6 #rest energy state of 1 proton bc it is the switchyard beam
        E_kinetic = 120E9 #beam energy
        E_tot = E_rest + E_kinetic
        gamma = E_tot/E_rest   #this gives us gamma bc energy cancels out, E_tot = gam
        ma*m*c^2
        print 'Gamma is '+str(gamma)

        Gamma is 128.931769723
```

RMS SCATTERING ANGLE DUE TO DIAMOND

In [5]:
```
#Beta represents the percentage of speed light that the beam is going
#Because of relativistic effects, a particle's velocity approaches the speed
#of light in vacuum, but it never actually reaches that velocity
```

$\beta = \frac{v}{c}$

In [6]:
```
#relativisitc factor equation
```

$\gamma = \sqrt{\frac{1}{1-\beta^2}}$

$\beta = \sqrt{1 - \frac{1}{\gamma^2}}$

In [7]:
```
#There is also relativistic momentum which is expressed as:
```

$p = \gamma * mc$

In [8]:
```
#Thus, the momentum can be calculated by: (units of eV/c)
```

$p = \frac{E_{total}}{c}$

RMS SCATTERING ANGLE DUE TO DIAMOND

In [9]:
```
#These equations are for factoring in the time, length and relativistic mass
#change for an object while it is moving. This is known as the Lorentz factor
#v is relative velocity, beta is ratio of velocity, v, to speed of light, c.
#We use the Lorentz factor since the beam is traveling really close to the spe
ed of light.
#So, we take into account for special relativity.
```

In [10]:
```
beta = (1-1/gamma**2)**0.5    #relativity equation
print 'Beta is '+str(beta)
print 'The beam goes at ' +str(beta*100) +'% of the speed of light.'
```

```
Beta is 0.999969921467
The beam goes at 99.9969921467% of the speed of light.
```

RMS SCATTERING ANGLE DUE TO DIAMOND

$$\Theta_{rms} = \frac{13.6\ MeV}{pv} z \sqrt{\frac{x}{X_0}}[1 + 0.038 ln(\frac{x}{X_0})]$$

In [11]:
```
#This equation is used for when a charged particle is traversing a medium
#(in this case the diamond material) for which causes small angle scatters.
#x/X_0 is the thickness of the scattering medium in radiation length
#x is the thickness of the diamond material
#X_0 is the radiation length of the diamond material, which has been measured
#and is a known number of 12.13 cm
```

In [12]:
```
c = 2.9979E8 #m/s, speed of light
v = beta*c #m/s, speed with relativity taken into consideration
p = E_tot/c # eV/c
print 'Momentum is ' +str(p)
```

```
Momentum is 403.409053004
```

In [13]:
```
x = 500E-6 #thickness of diamond, in meters
X_0 = .1213 #radiation length of diamond, in meters
z = 1 #this is the charge number of proton beam
```

RMS SCATTERING ANGLE DUE TO DIAMOND

In [14]:
```
import math
theta_rms = ((13.6E6)*((x/X_0)**0.5)*(1+.038*math.log(x/X_0)))/(p*v)
print 'Theta_rms is ' +str(theta_rms)
print 'The scattering angle of the Diamond Detector is ' +str(theta_rms*10**6)
 +' microradians.'
```

```
Theta_rms is 5.71346239686e-06
The scattering angle of the Diamond Detector is 5.71346239686 microradians.
```